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Translated by A. B. Dunn

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Abstract

Spectra of an intense impulsive discharge in hydrogen have been obtained by means of a spectrograph with a diffraction Echelle-grating (dispersion 1.5 A/mm). A spectrophotometric study of the broadening of hydrogen emission wings (H_α - H_ε) gives the following results:

a) When observing the spectra of a self-contracted discharge in a perpendicular direction the emission of hydrogen line wings (extending to 30-40A) is broadened due mainly to the linear Stark effect (the initial pressure p_0 = 0.1 mm Hg).

b) At p_0 = 0.5 mm Hg the emission extends to 50-80 A and is broadened in the wing, probably due mainly to the quadratic Stark effect.

c) When the spectra are observed along the plasma discharge the broadening of hydrogen emission in the wings is due to macroscopic plasma motions with velocities $\sim 10^8$ cm/sec. The intensity variations in the wings are well explained by the supposition on directed plasma motion of the jet type along the axis of discharge with velocity gradients.

d) In observations outside the axis of discharge the broadening of hydrogen emission (at p_0 = 0.1 mm Hg) in the transversal as well as the longitudinal direction (near the discharge) is wholly due to the linear Stark effect.

A comparison of the above results with data on emission broadening in lines of solar flares points to an analogous cause of broadening and a relation between the character of broadening and the direction in which observations are made.

INTRODUCTION

Spectra of hydrogen emission in solar flares show a remarkable likeness to spectra of high-temperature hydrogen plasma glowing in impulsive discharges of great intensity; in both cases there are observed bright and extended wings of lines (see for example Fig. 3) and also a sharp fall of the "strength" of lines (total energy emitted in the line) with number of the member of the Balmer series. This circumstance, and also some facts and considerations testifying to more profound analogies (if there is no resemblance or likeness - see for example [1]) between solar flares and laboratory pinch-effect (self-contraction of current-discharge) prompted us to conduct investigations of spectra of intense impulsive discharge in hydrogen by those methods that we found more or less successful in the study of the physical processes on the sun. Possibly, the similar application of specific astrophysical methods and modes will turn out to be useful also for the determination of important diagnostic problems of the state of laboratory high-temperature plasma.

Spectroscopic studies of intense impulsive discharges in hydrogen were carried out in works [2,4], but the use of spectral instruments of low dispersion and resolving power (ISP-51) appreciably limited the possibility of studying these profiles of hydrogen emission of plasma, with the exception of the very broad line H_α, the wings of which, according to [3], stretch to 20 A.

Preliminary scanning of the spectra (see [3]) indicates that similar broad wings arise only at the moment of "first apparition" (time 1 microsecond) - the

moment of maximum compression of plasma discharge (first dip in oscillogram current). At this same moment a flare-up of continuum occurs, owing its origin to the braking of radiation of free electrons in the plasma. Until the moment of maximum compression and after it, the broad wings of H_{α} are practically absent, and the halfwidth of the line is on the order of several Angstroms. This circumstance makes possible the study of causes of broadening of wings of lines by means of photography of discharge spectra during the whole time of its existence (without use of preliminary scanning), and even - by means of consecutive photography of some discharge - the positive check on its identity (as regards compression in the chamber and oscillogram current). In its turn, this considerably facilitates the possible use of spectral instruments with large dispersion and high resolving power, and this allows us to conduct accurate photometric studies of profiles of hydrogen emission, bearing in mind the far wings.

The central part of the profile, in regions several Angstroms from the center of the line, is formed, apparently, as a result of superposition of emissions occuring in various stages of development of discharge, and probably having different characters; hence, remembering this effect of superposition, it is necessary to have care in drawing any conclusions on the central portion of the profile obtained by such "integration" according to time.

First, in the present work, we examine the problem of broadening of hydrogen emission up to the point where success of further quantitative analysis is impossible without knowledge of the mechanism of broadening of spectral lines. Although there exist repeated qualitative indications that here broadening of hydrogen emission is caused by linear Stark effect, it would be impossible to exclude, a priori, the possibility of the effect of other mechanisms connected with motion in plasma - "turbulence," and other causes having a character of collective reciprocity. Besides, the possibility is not excluded of difference of mechanism of broadening in various sections of plasma discharge and in various directions relative to the axis of discharge. All of these considerations were taken into account in carrying out the experiments (see Section 2).

1. APPARATUS AND METHODS OF MEASUREMENT

The instrument for obtaining discharge (similar to that described in [2]) consists of capacitor battery 16 with general capacity C = 32.4 microfarads charged to voltage U_0 = 30 kv (Fig. 1). The periodically damped discharge inside chamber 9 is excited by the impulse voltage feed on the discharge apparatus. Discharge chamber 9 is manufactured from ceramic tubing with an inside diameter of 400 mm the distance between electrodes 14 and 15 is 980 mm. In one of these electrodes, 15, there are openings for observations of discharge along the axis of the chamber. In the chamber are mounted two nozzle-type fittings on one side (12,13) and two at the end (10,11). One of these allows us to observe plasma on axis (lengthwise and across) and the other - to one side of the plasma discharge (along the axis of the chamber or across). Chamber 9 is surrounded coaxially by a copper cylinder for reduction of inductance in the oscillatory circuit. Capacitor battery 16 is charged by a high-voltage rectifier. The current passing through the chamber is measured by integration of Rogovski zones. The relation of current to time is recorded by the impulse oscillograph OK-17 (18). Filling the cell with hydrogen is carried out by the system for filling and filtering 20, containing a palladium filter-accumulator and reservoir for gas dosage. As a preliminary the cell is evacuated to 10^{-5} mm Hg. Natural leakage in the cell takes place due to generation of gas by the wall of the chamber, and does not exceed 0.05 μ mcn/sec. Before the experiment the cell was prepared for de-aeriation of the wall by a series of discharges. The usual value of amplitude of discharge current was around 500 ka.

Discharge was studied with the aid of an Echelle spectrograph, the basic elements of which (1-6) are given in Fig. 1. Radiation in the studied contents of the discharge chamber is projected on slit 6 of the spectrograph by means of plane mirrors 8 and 7, so that concave collimator mirror 5 (with specially selected relative aperture $d = 10$ cm, $f = 5$ m) is filled with light only from the contents of the discharge chamber, yielding a cylinder of diametor ~ 4 cm (order of the dimension of compressional discharge) in the direction of line of sight. A parallel pencil of rays from the collimator mirror falls on the Echelle diffraction grating 4 (described in [5]) with a concentration of light in the 39th to 65th order for visible parts of the spectrum, and thence passes twice through prism 3 of fused quartz, with a refractive angle of 12°. The prism served to attenuate various orders in a direction perpendicular to the direction of the dispersion of the Echelle, and let pass all emission with wavelength $\lambda > 2000$ A. The image of the spectra obtained in this way was formed on photoplate 1 by cell mirror 2 in its focal plane.

On Fig. 2 is given an example of discharge spectra obtained on the Echelle spectrograph with initial pressure $p_0 = 0.5$ mm Hg (observation along axis of discharge). On Fig. 3 to the left are given enlarged photographs of Balmer lines of discharge ($p_0 = 0.1$ mm Hg, observations perpendicular to axis of discharge) and to the right - photos of the same lines in spectra of intense solar flare of 20 VII, 1959. Spectra clearly show all Balmer lines from H_α to H_ε (sometimes H_ζ is outlined) and a number of other lines in admixtures. Spectrograph dispersion in the red part is 1.9 A/mm. The limiting resolving power of the spectrograph (half-width of instrumental profile) is 0.25 A.

We see that the wings of hydrogen lines are very broad and stretch to 50-70 A (for H_α), so that in order to obtain correct, non-distorted profiles it is not necessary to use the narrow slit of the spectrograph. If, in the solar spectrum, lines with widths of ~ 0.2 A can be obtained without distortion caused by smoothing (because of the finite slit width) with slit width of 0.02 A (equal to width of instrumental profile), then for broad hydrogen emission of discharge a suitable slit width will be $\sim 0.5 - 1$ A in the focal plane of the spectrograph chamber ($\sim 1/10$ halfwidth of lines that are 5 - 10 A); for a dispersion of 2 A/mm this gives 0.25 - 0.5 mm for projection of the slit in the chamber, and since the focal distance of the chamber is roughly 2.5 less than for the collimator, the width of the entrance slit will be 0.6 - 1.2 mm.

We worked with an entrance slit equal to 0.5 mm. Thus the distortion due to smoothing of the profile owing to the finiteness of slit-width will not be greater than the usual photometric error for solar lines. We should point out that line profiles we obtained with a wide slit equal to 4 mm (~ 3 A on the plate) show considerable distortion: the wings were more gentle than with a "normal" slit, and were more gentle the narrower the line (for example H_δ , H_ε) since here distortion due to smoothing naturally counts more than for lines so wide as H_α .

The great width of hydrogen lines makes necessary a calculation of possible distortion of profiles connected with the effect of vignetting of the field by change of spectral sensitivity of the plate in part of the spectral lines, by changes, in this part, of the concentration of light in a given order of the Echelle, and by other possible photometric non-uniformities of the field. All of the errors can be calculated if we carry out photometry of spectra of some source of light with known distribution of intensity. We used the center of the solar disk as such a source, the spectrum of which was photographed on the same spectrograph by means of the coelostat instrument of the spectrohelioscope, in which the entire system was accommodated. For formation of the solar image a mirror was used on the spectrograph slit, so that the distribution of intensities in the solar spectrum did not undergo distortion in the studied band of the spectrum.

Distribution of intensities in the solar spectrum is taken according to Mulder's average curves [6].

The distribution of intensities in the solar spectrum, measured according to calibration spectrograms, gives us, - within the limits of each spectral band of the Echelle-, some function in the form

$$I_{\odot}(\lambda) / I_{\odot}(\lambda_0) = k_1,$$

if intensity is expressed in units of intensity for wavelength λ_0. On the other hand, according to Mulder's curves, we establish function

$$I(\lambda) / I(\lambda_0) = k_2,$$

which would take place in the absence of photometric errors in the field. Ratio k_2/k_1 is some reduction factor; it was constructed graphically for all portions of lines around 150 A containing the studied lines H_α - H_ε . By means of such reduction curves we can find the distribution of intensities free of the influence of photometric and instrumental errors of the field. If the profiles are asymmetric and have irregular form without the calculation of these errors, after calculation they are even and practically symmetrical. Similar calculation of errors is very essential for correct judgement of asymmetry connected with motion of plasma

Calibration of spectrograms requires an exposure of step-wedges with the same exposures as the duration of the discharge ($\sim$10 microseconds). The main portion of the spectrogram is processed by means of characteristic curves obtained by direct photography of the discharge. Toward this goal plate HP-3 (with the same sort of emulsion as that on which spectra were photographed and with close step-wedges and coloured filters superimposed on it) was mounted at a distance around 2 m from the window of the discharge chamber, and this plate was lit up by radiation of discharge without use of projective optics. For processing of portions of the first spectrogram we used characteristic curves obtained by photography of the center of the solar disk on the solar telescope BST through a step-wedge and coloured filter, with exposure of around 100 microseconds.

In all of the present work there was no need to find absolute intensities. Intensities of all lines for each plate are expressed in units of central intensity of line H_δ (In those cases where discharge was photographed several times, the central portion of lines so intense as H_α and H_β were found to be overexposed, which made difficult the presentation of profiles in units of central intensity of the same line; hence the intensity of the center of H_ε , the photographic density of which always fell in the middle portion of the characteristic curve, was taken as unity.)

In cases where an emission line is observed on the background of continuum, as is noticeable on the spectra taken with high compression (0.5 mm Hg), correct calculation of the background is necessary. Calculation of the background is carried out by means of photometry of spectra of adjacent orders not containing broad lines; for these are obtained distributions of intensity free of photometric errors of field (as in cases of portions containing lines), and thereupon averages are calculated for two bands to the blue and red sides of the given one. This distribution (see for example, Fig. 7) is calculated from distributions for studied portions containing emission of hydrogen lines.

2 DISTRIBUTION OF INTENSITIES IN WINGS OF BALMER LINES

The program of measurement provided for obtaining a series of spectra across the axis of discharge (mark ⊥) both in the center (in the direction on-axis - "center") and on the periphery of discharge (to one side of axis - "off-center"), and also a series of spectra along the axis (mark ∥) both along discharge ("center") and parallel to the axis but to one side of discharge ("off-center") on the periphery of the discharge. In a majority of cases it was necessary to take from 3 to 5 discharges successively on each plate in order to obtain all lines (H_α - H_ϵ) and to construct reliable curves of lines. For verification of the effect of compression, such a series of measurements was done for compression p_0 equal to 0.1 and 0.5 mm Hg. All data on the processed spectra are given in Table 1. Here in the first column is shown how the observation was carried out with respect to the axis of discharge, in the second is given the plate number, in the third the number of discharges on the plate; in succeeding columns are contained results of the measurements (see below).

Table 1

Pinch	Plate No.	No. of Discharges	Coefficient of inclination of straight line k H_α	H_β	H_γ	H_δ
			Pressure p_0 = 0.1 mm Hg			
⊥ center	4	1	1.5	2.3	2.2	2.6
⊥ center	113	20	2.5	2.4	2.3	1.9
⊥ center	118	5	2.2	2.3	2.1	2.3
⊥ center	131	5	2.2	2.0	2.2	1.8
∥ center	114	5	Sharp deviation from Stark broadening.			
∥ center	135	5	Broadening of emission caused by macro-			
∥ center	146	5	scopic motion of plasma			
⊥ off-center	117	5	2.9	2.9	2.3	2.1
⊥ off-center	133	5	2.6	3.2	2.6	-
⊥ off-center	134	5	3.1	2.7	2.7	-
∥ off-center	104	5	2.8	3.0	1.9	2.5
∥ off-center	143	5	2.4	3.1	2.4	1.9
∥ off-center	144	5	2.4	3.2	3.6	-
			Pressure p_0 = 0.5 mm Hg			
⊥ center	173	3	1.6	1.9	2.3	2.2
⊥ center	178	3	1.6	1.9	1.7	-
⊥ center	179	3	1.6	1.7	-	-
∥ center	157	3	Sharp deviation from Stark broadening.			
∥ center	158	3	Broadening of emission caused by macro-			
∥ center	159	3	scopic motion of plasma			

On Fig 4 are given, as examples, profiles of Balmer emission from the center of discharge (self-compressed discharge) for observations across and along the axis of the chamber, obtained with compression p_0 = 0.1 mm Hg. Direct comparison of profiles of emission in discharge obtained across the axis with profiles obtained along the axis shows considerable difference in them: a) the intensity of wings by comparison to central intensity of lines H_α and H_β, i.e. relative width of the wings of lines for observations along axis is appreciably greater than for observations across (H_α for transverse discharge is over-exposed in the center since its central intensity is roughly 60 times greater than the intensity of

H_γ ; the scale of intensities for H_δ and H_ε is enlarged 5 times); b) since all intensities are expressed in units of central intensity of H_δ (= I_0), the decrement of the Balmer series for observations across the discharge is considerably greater than for observations along the discharge; c) in some cases lines H_α and H_β show absorption drops in the center of the line, which indicate the important role of self-absorption (along the axis the optical thickness of the discharge is of the order of unity)

For quantitative analysis of the causes of broadening of emission, all profiles were considered in coordinates ($\lg I/I_0$, $\lg \Delta\lambda$) and ($\lg I/I_0$, $\Delta\lambda^2$). The profiles in these coordinates are given in Fig. 5 and 6, and show considerable difference in the run of intensity with distance from center of the line for cases of observations across the axis (Fig. 5) and along the axis (Fig. 6). If in the first cases in coordinates ($\lg I/I_0$, $\lg \Delta\lambda$) the run of intensity in the wings of lines nicely corresponds to a straight line with angle of coefficient 2.2 - 2.4, in the second case the run of intensity in the wings is practically impossible to represent by a straight line. (In some cases the run of intensity is drawn separately for blue and red wings of lines; the difference in run is probably connected with small errors in photometry.)

If one nevertheless attempts to represent this run by a straight line, the angle of coefficient will be near unity. At the same time, in axes ($\lg I/I_0$, $\Delta\lambda^2$) an opposite picture is observed: for observations along the discharge the run of intensity in wings is near to a straight line, whereas for transverse observations of discharge this run differs considerably from a straight line. From Table 1 we see that a similar situation with lengthwise and transverse observations takes place for all other spectrograms. This indicates that with compression p_0 = 0.1 mm Hg the emission broadening in the wings of hydrogen lines is connected with linear Stark-effect for observations across the axis of discharge, whereas along the axis of discharge it is caused, on the whole, by Doppler effect.

In the case of strict "Doppler" profile $I \sim e^{-(\Delta\lambda/\Delta\lambda_D)^2}$ we would have to obtain a straight line in coordinates ($\lg I/I_0$, $\Delta\lambda^2$). At the same time, there are some small deviations, which can be nicely explained by the presence of directional motion of the "jet" type along the axis of discharge with some gradient of velocity along the "jet." According to [7] the distribution of intensities in this case can be represented in the form

$$\frac{I}{I_0} \sim \ln \frac{\Delta\lambda_m}{\Delta\lambda} \tag{1}$$

where $\Delta\lambda_m$ is the "width" of the wing of the line corresponding to a maximum velocity of motion of atoms in the "jet." Crosses and plusses in Fig. 6 show the sum of intensities according to formula (1), selected from conditions of best agreement of observed and calculated profiles. We see that an idea of jets with velocity gradients agrees well with observed distribution of intensities in wings of Balmer emission observed along the length of discharge. Values $\Delta\lambda_D/\lambda$, determined for the run of intensity in the wings, and also values $\Delta\lambda_m/\lambda$, are given in Table 2. In spite of separate random deviations (connected, on the whole, with the difficulty in calculating background, see above), correlations $\Delta\lambda_D/\lambda$ = const or $\Delta\lambda_m/\lambda$ = const are fulfilled in transition from one emission line to another, as must be so in the case of broadening due to macroscopic motion. Of course the question of the contribution of Stark effect in observed profiles of wings of lines in the given terms remains open.

Table 2

Plate No.	$\frac{\Delta\lambda_D}{\lambda}\cdot 10^3$					$\frac{\Delta\lambda_m}{\lambda}\cdot 10^3$				
	H_α	H_β	H_γ	H_δ	H_ϵ	H_α	H_β	H_γ	H_δ	H_ϵ
	Pressure p_0 = 0.1 mm Hg									
114	3.3	1.5	1.7	1.5	1.3	5.2	-	3.3	2.7	2.0
135	4.7	2.9	5.5	2.5	2.7	9.6	7.0	9.7	4.9	4.8
146	4.6	1.9	2.4	2.3	2.2	7.7	3.3	4.3	3.8	3.5
	Pressure p_0 = 0.5 mm Hg									
159	6.6	6.9	8.2	7.8	6.0	11.8	13.6	13.8	12.8	-

For a more precise definition of this, we made a series of similar measurements with higher compression (p_0 = 0.5 mm Hg). The results of these measurements are given in Fig. 7 (line profiles) and Fig. 8 and 9 (logarithmic profiles) similar to Fig. 4, 5 and 6. With compression of 0.5 mm Hg the line becomes considerably broader (notice the change in scale of wavelength and of relative intensity in Fig. 7). Here the wings of line H_α stretch farther than 100 A, and for lines so weak as H_ϵ they are observed out to 40-50 A. Here the centers of intense lines (H_α, H_β) are always overexposed, hence it is difficult to judge the decrement and to compare widths for observations along and across the discharge, but weak lines (H_δ, H_ϵ), as in cases of low compression, show that the wings of lines in observations in a lengthwise direction are appreciably broader than in a transverse direction. Logarithmic profiles (Fig. 8, 9) show that it is possible to represent the run of intensity in wings of lines (for observations across discharge) by a straight line in coordinates ($\lg I/I_0$, $\lg \Delta\lambda$) with angle of coefficient of roughly 1.6 to 2.0 with an average $\sim$1.8, although deviations from a rectilinear relationship are somewhat greater here than with low compression. Deviations from a straight line in axes ($\lg I/I_0$, $\Delta\lambda^2$) are quite apparent in these cases (right side of Fig. 8). This allows us to consider that broadening of hydrogen emission in transverse observations in the case of high compression as well as in low compression is connected, on the whole, with Stark effect, and not with the effect of macroscopic motion, although possibly the latter effect plays some role in this case.

Representation of line profiles in axes ($\lg I/I_0$, $\Delta\lambda^2$) in the case of lengthwise observation of discharge (Fig. 9) shows that, as in the case of lower compression, the run of intensity in wings of lines can be explained by the presence of motion of the "jet" type. The systematic increase of $\frac{\Delta\lambda_D}{\lambda}$ and $\frac{\Delta\lambda_m}{\lambda}$ for higher compression is apparently connected with the fact that with great compression Stark effect begins to play a certain role in broadening for observations along the axis of discharge, resulting in an effective increase of $\Delta\lambda_D$ and $\Delta\lambda_m$.

During the photography of spectra of central portions of discharge, emission of rarified plasma located in the same line of sight as the compressed discharge also falls on the slit of the spectrograph. This plasma radiates at the start of discharge and also with the decay of the discharge, and exists for a longer time than the compressed discharge. In order to explain the contribution of this portion of plasma in the formation of the lines considered, spectra of

discharge were photographed through the lateral windows of the cell (13 and 11 on Fig. 1) with compression $p_0 = 0.1$ mm Hg. Thus radiation of the discharge itself did not fall on the slit of the spectrograph. Profiles of hydrogen emission in spectra taken perpendicular to and parallel with the axis of the cell, and to one side of the discharge, are given in Fig. 10. First of all we should note that hydrogen emission in this case is considerably weaker than discharge emission (photographed through the central window of the discharge cell). In addition, the wings of lines on these spectrograms are considerably less extensive than in cases considered earlier, especially in spectra taken perpendicularly to the axis of discharge. From Fig. 11, on which the same profiles are drawn in logarithmic scale, it is obvious that wings of lines are very nicely represented by straight lines with coefficient of inclination on the average of 2.5 for spectra photographed perpendicularly to the axis of discharge, and 2.8 for spectra photographed parallel to the axis of discharge.

Thus, to the wings of lines of hydrogen emission of the compressed discharge is added the several-times-less intensity due to radiation of rarified plasma. The run of intensity of the additional emission has a steeper drop than the run of intensity in wings of lines radiated by compressed discharge. Consequently, the additional emission does not actually distort the distribution of intensities in wings of hydrogen lines occurring in the central portions of the discharge. At the same time, it can cause considerable variation in distribution of intensities near the central portions of lines.

3. DISCUSSION OF RESULTS

As has already been noted, profiles of wings of hydrogen lines in axes ($\lg I/I_0$, $\lg \Delta\lambda$) obtained by transverse observation of discharge are nicely represented by a straight line. Thereby, as follows from Table 1, the angular coefficient k of inclination of straight lines averaged for all lines studied on several spectrograms in each series is equal to: a) $k_{av} = 2.7$ for observations outside the axis of discharge ($\perp$ & $\parallel$ "off-center"); b) $k_{av} = 2.2$ for observations across axis of discharge ($\perp$ "center") with initial compression $p_0 = 0.1$ mm Hg, and c) $k_{av} = 1.8$ in an analogous case with $p_0 = 0.5$ mm Hg. The stated difference in angular coefficient can be explained by the action of Stark effect.

Consideration of Stark effect, taking into account broadening effect of electrons, is given in [8] and [9]. On Fig. 12 dashes show the theoretical distribution of intensities in wings (in system $\lg I$, $\lg \Delta\lambda$) according to V. N. Kogan's data ([8], p. 285), from which it follows that in the wings of the lines the average coefficient $k \approx 2.7$ if this distribution can approximate a straight line (which can be done with an accuracy of up to ~ 0.1 in $\lg I$, i.e., with accuracy to $\sim 25\%$). According to [9], a profile broadened due to Stark effect by combined action of ions and electrons is determined by the function $T(\Delta\lambda, \gamma)$ where γ is the parameter characterizing the influence of electrons,

$$\gamma = 5.6 \cdot 10^{-6} N^{1/3} T^{-1/2} \left[\lg \frac{4 \cdot 10^6 T}{b^2 N^{1/2}} - 0.125 \right] \frac{b^5 + a^5}{b^2 - a^2} \qquad (2)$$

(T and N are temperature and density of charged particles, b is the main quantum number for the upper, a for the lower level). Assuming as an estimate in our case $T = 5 \cdot 10^5$, $N = 5 \cdot 10^{15}$ cm^{-3}, we obtain the following values of γ: for H_α +0.09, for H_β +0.32, for H_γ +0.52, for H_δ +0.82, i.e., all values of γ are confined within the interval $0 < \gamma < 1$.

On Fig 12 is shown the run of intensity according to ([9], Table 3) for $\gamma = 0$ (dots), $\gamma = 0.5$ (plusses) and $\gamma = 1.0$ (circles). In the wings these distributions are nicely represented by a straight line with average coefficient $k = 2.67$, which agrees with the theoretical distribution [8]. Hence we can consider that the theoretical profile, taking into account broadening by electrons, gives $k = 2.7$ Good agreement with this distribution is obtained only for the periphery of discharge (outside of line of discharge) both in lengthwise and transverse observations. As regards observations across the very line of discharge (observations in the center), here we obtain a coefficient k systematically less than 5/2 (~ 2.2) for low (0.1 mm Hg) compression and still less (~ 1.8) for high compression.

For intermolecular fields $F_n > 10^5$ v/cm quadratic Stark effect begins to play a role since

$$F_n = 2.6eN^{2/3} \approx 3.8 \cdot 10^{-7} N^{2/3} \text{ v/cm}, \qquad (3)$$

so that the role of this effect remains appreciable; in other words where $N \geqslant 10^{17}$ cm^{-3}; in our case, with compression 0.5 mm Hg value $N \approx 1.5 \cdot 10^{16}$cm^{-3} with ionization roughly equal to 1. If there occurs $5 \div 10$th compression in the core of the discharge, then the number N can be on the order of $5 \div 10 \cdot 10^{16}$; i.e., quadratic Stark effect can play some role for compression ~ 0.5 mm Hg. In this case the distribution of intensities $I \sim \Delta\lambda^{-7/4}$, and in the wings it will be a more gentle path close to $\Delta\lambda^{-2}$, which is actually observed. In the case of low compression (0.1 mm) this effect plays a lesser role, and distribution of intensities in wings must be nearer to that given by linear Stark effect ($k = 2.5$). Thus we could explain the deviations from strict theoretical dependence for Stark effect taking into account the broadening effect of ions and electrons.

However, it is impossible to explain the gentle wings, low values of k and sharp deviations from rectilinear dependence for observations along the axis of discharge by means of an assumption of broadening by Stark effect only. In this case the run of intensity in wings of lines, as has already been pointed out, is well described by the assumption of the existence of directional motion of the jet type with a velocity gradient. The values $\Delta\lambda_D/\lambda$ and $\Delta\lambda_m/\lambda$, presented in Table 2, allow us, first of all, to determine the constituent "Doppler" velocities of motions of atoms along the axis of discharge, and, second, to find the maximum velocity in "jets" according to (1). With initial compression $p_0 = 0.1$ mm Hg, the average value of $\frac{\Delta\lambda_D}{\lambda} \approx 3 \cdot 10^{-3}$, which corresponds to $v_D = 9 \cdot 10^7$cm/sec. For this same case the average value $\frac{\Delta\lambda_m}{\lambda} \approx 5 \cdot 10^{-3}$, from which we obtain the maximum velocity of motion of atoms in a jet of $v_m = 1.5 \cdot 10^8$ cm/sec.

The process of outflow of plasma of jets from the aperture in the lower electrode (through which observation along the axis is carried out) can introduce some contribution to broadening of lines in experimental observations. Possibly this points to some systematic predominance of emission in the blue wings of the majority of Balmer lines (Fig. 6). Thus, apparently, the experimental data obtained from analysis of the distribution of intensities in wings of Balmer lines with observation along the axis of the system indicates the existence, in the discharge, of groups of hydrogen atoms which are in rapid motion. The energy of these atoms attains 5-7 kev. We should keep in mind, however, that we run into some difficulty in the discussion of such effects that result in proposed interpretations of experimental data. If the observed form of a line

profile serves as optical evidence of the existence of a current or jet of rapid particles, then, irrespective of the mechanism of origin of rapid particles, there must be other indications of the presence of these atoms. In particular, in discharge of deuterium there must be observed a nuclear reaction of synthesis and subsequent neutron radiation. As is well known, plasma-neutron effect and neutron radiation were indeed discovered earlier, in 1952. However, this radiation is observed, as a rule, in the moment of second compression of plasma discharge, and not at the moment of first compression when, according to data of optical scanning, the maximum line broadening is observed.

Undoubtedly further experiments are necessary to elucidate this question.

The mechanism of broadening of hydrogen emission with intense impulsive discharge is very similar to that which is given detailed study ([1,7] and others) in broadening of emission lines in solar flares. In both the first and possibly the second cases the run of intensity in wings of lines depends considerably on which direction the observation of spectra of plasma radiation is carried out. This, in particular, allows us to infer that there probably exists an analogy, based on the close physical nature of the phenomena, between intense impulsive discharge carried out in the laboratory and the occurrence of chromospheric flares on the sun.

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Figure Captions

Fig. 1. Diagram of instrument.

Fig. 2. General form of discharge spectra with observations along the axis (p_0 = 0.5 mm Hg).

Fig. 3. Hydrogen lines in discharge spectra (a) for observations perpendicular to axis (p_0 = 0.1 mm Hg) and (b) in spectra of chromospheric flare of 20, VII 1959.

Fig. 4. Profiles of hydrogen lines in discharge spectra with initial compression p_0 = 0.1 mm Hg (left - observations perpendicular to axis, plate 113; right - along axis, plate 146).

Table 1

Pinch	Plate No.	No. of shocks	Coefficient of incline of straight line k
		Compression p_0 = 0.1 mm Hg	
			Sharp deviation from Stark distribution. Emission broadening caused by macroscopic motion of plasma
		Compression p_0 = 0.5 mm Hg	
			as above

Fig. 5. Logarithmic profiles of hydrogen lines in discharge spectra with observations perpendicular to axis (plate 113).
Dots and circles - observations for blue and red wings of line respectively.

Fig. 6. Logarithmic profiles of hydrogen lines in discharge spectra with observations along axis (plate 146).
Dots and crosses - observations and calculations ("jets") respectively for blue wing of line; circles and +'s - observations and calculations ("jets") for red wing of line.

Fig. 7. Profiles of hydrogen lines in discharge spectra with initial compression p_0 = 0.5 mm Hg (left - plate 173; right - 159).

Fig. 8. Logarithmic profiles of hydrogen lines in discharge spectra with observations perpendicular to axis (plate 173).
Designations same as in Fig. 5.

Fig. 9. Logarithmic profiles of hydrogen lines in discharge spectra with observations along axis (plate 159).
Designations same as Fig. 5.

Fig.10. Profiles of hydrogen lines in discharge spectra (p_0 = 0.1 mm Hg) with observations outside of axis of discharge, and parallel to it (left - plate 133, right - 104).

Fig.11. Logarithmic profiles of hydrogen lines with observations outside of axis of discharge (left - perpendicular to axis, plate 133; right parallel to axis, plate 104).

Fig.12. Theoretical distribution of intensities in wings in the case of line broadening due to Stark effect.
Dashed line - Kogan's data, solid line - Griem's data.